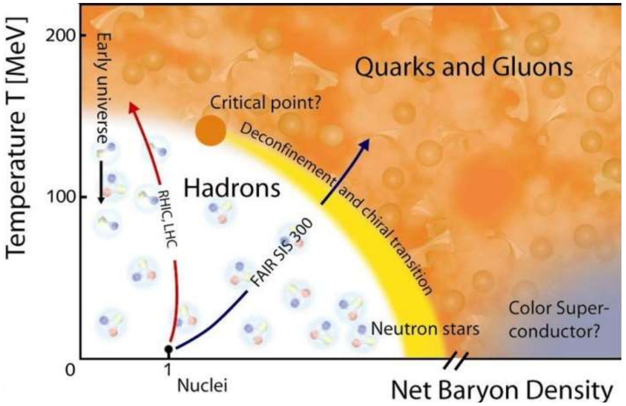
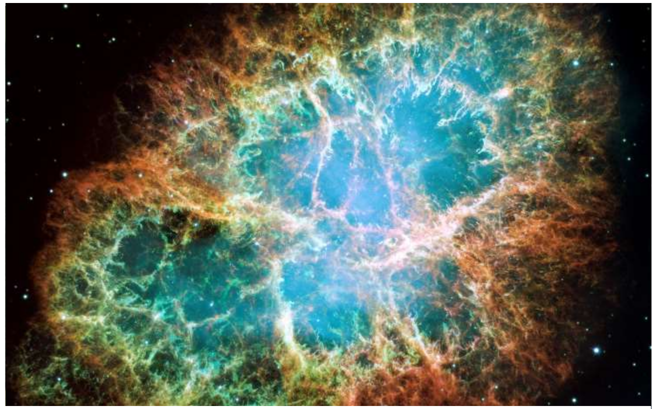


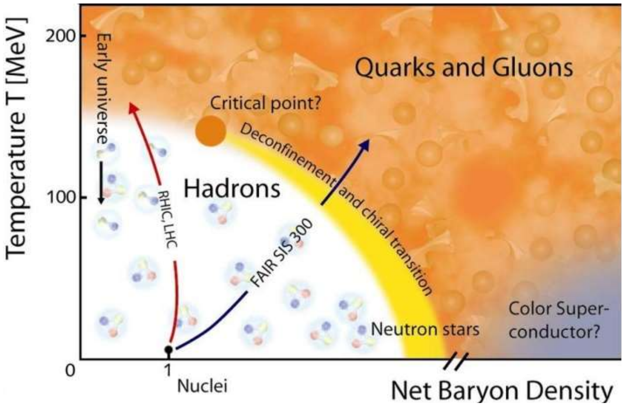


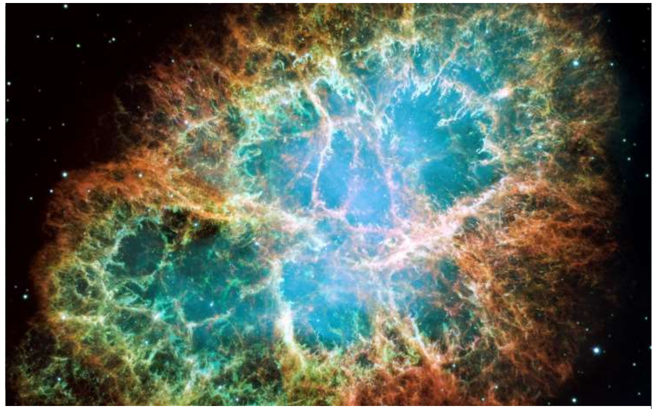
Constraining the EOS of strongly interacting matter in heavy ion collisions

Y. Leifels

GSI Helmholtzzentrum für Schwerionenforschung GmbH Darmstadt

EMMI Rapid Reaction Task Force
The physics of neutron star mergers
Symposium
8.6.2018



or… Squeezing the symmetry energy out of heavy ion reactions

Y. Leifels

GSI Helmholtzzentrum für Schwerionenforschung GmbH Darmstadt

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The physics of neutron star mergers
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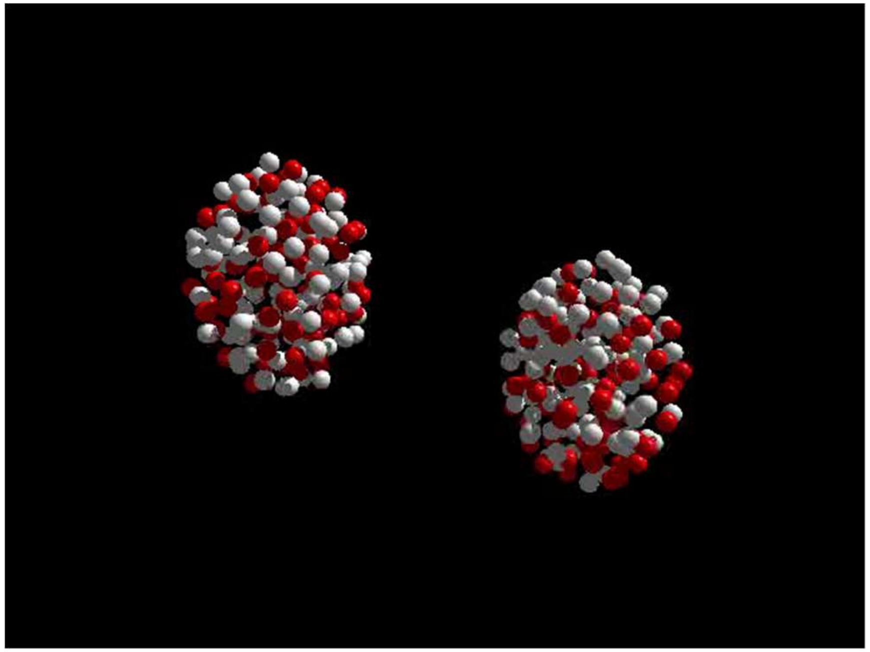
Introduction

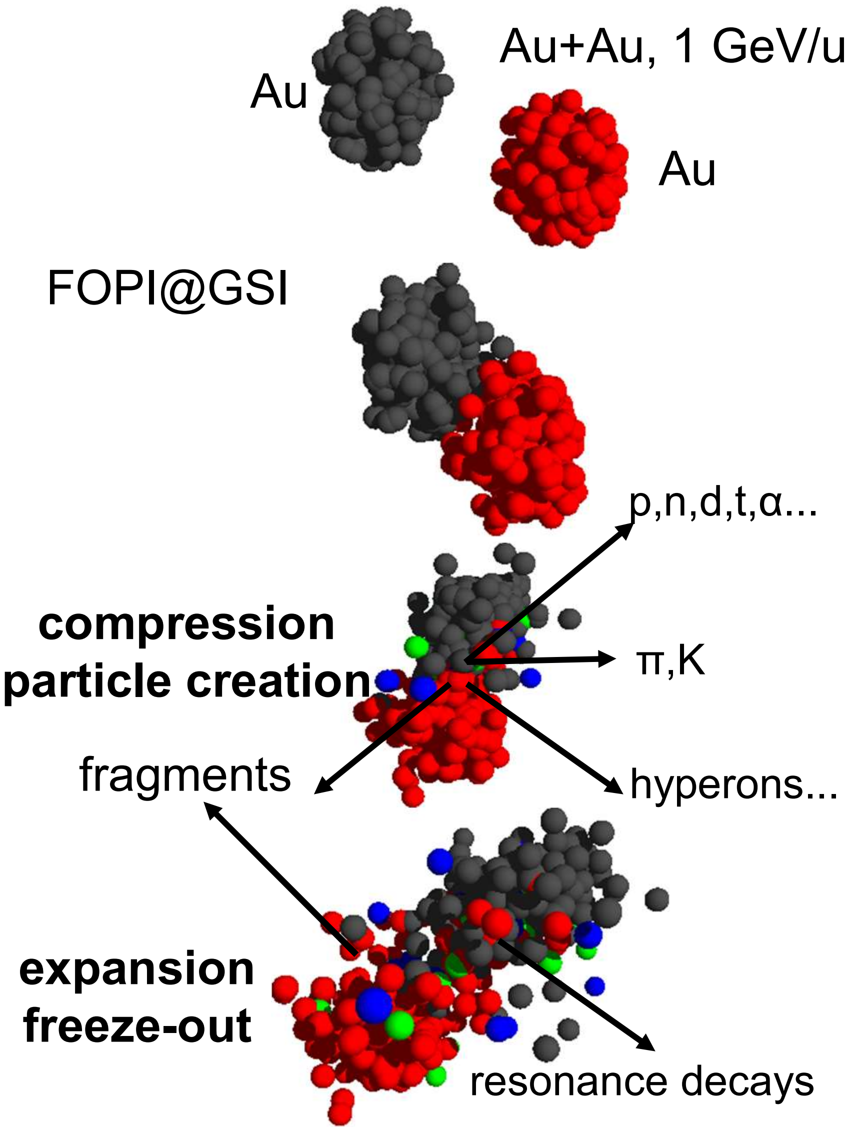


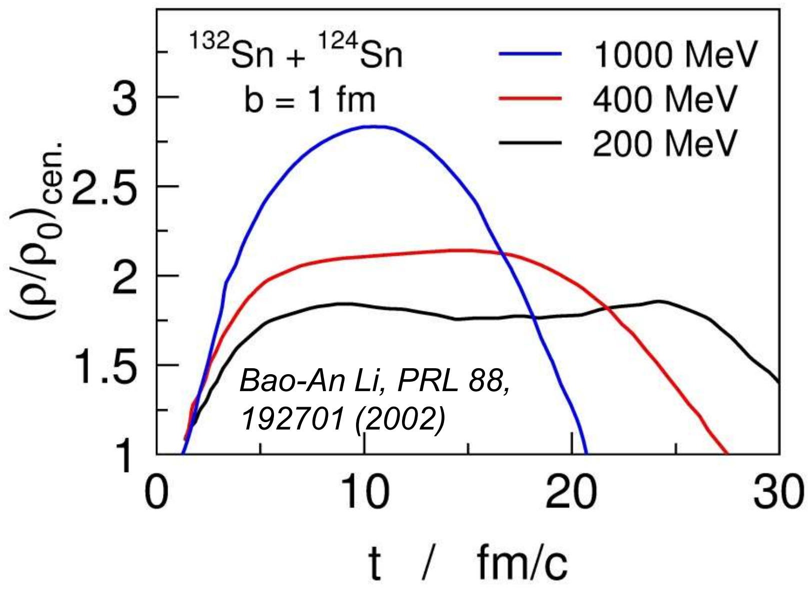
Au+Au 1.5 AGeV UrQMD

- neutron star mergers: T = 0-100 MeV, $\rho = 10^{-3} - 10\rho$
  - mass: ~ $4 \cdot 10^{30}$ kg
  - size: ~$2 \cdot 10^{4}$ m
- neutron stars: T = 0, $\rho = 10^{-3} - 5\rho_0$
- supernovae simulations: T = 1-50 MeV, $\rho = 10^{-10} - 2\rho_0$

- heavy ion reactions: T= 5 MeV – >180 MeV, $\rho = 10^{-3} - 5\rho_0$
  - mass: $6.540 \cdot 10^{-24}$ kg
  - size: $2 \cdot 10^{-14}$ m
  - life time: 3 -100 $\cdot 10^{-24}$ s

HICs: Characteristics at 0.1 – 10 GeV/u

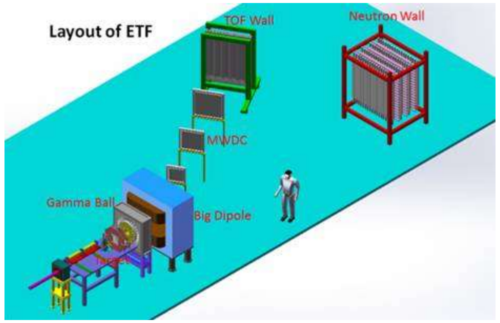


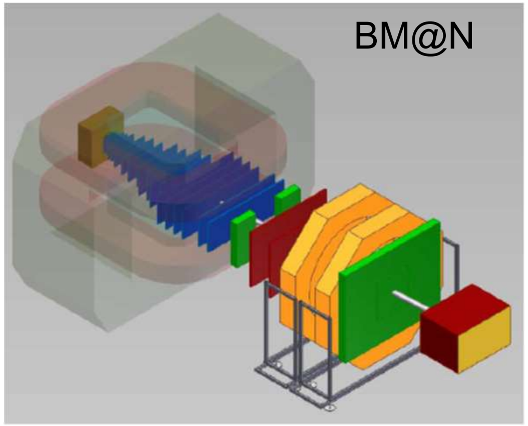


- reaching high densities, several ρ_0
- creating (thermal) pressure
- controlling density and pressure by varying system size and/or energy

Experiments

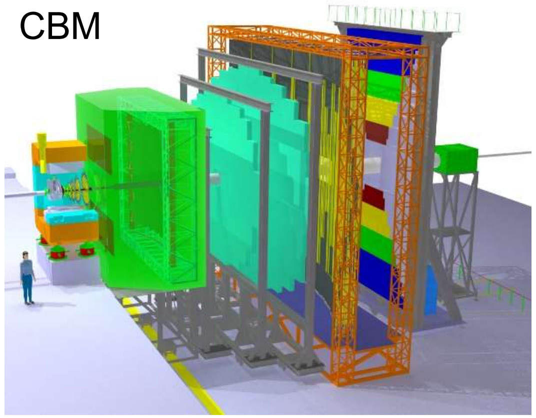
ETF@IMP



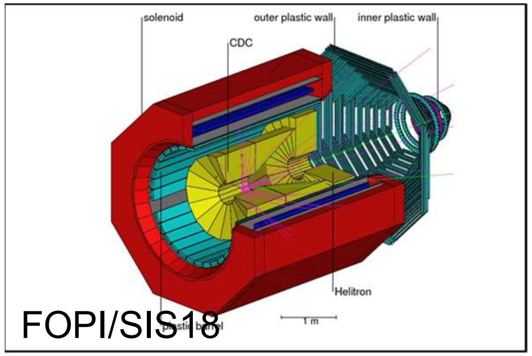


BM@N

CBM

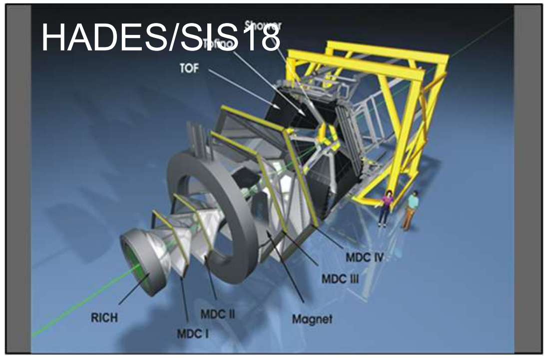


KAOS/SIS18



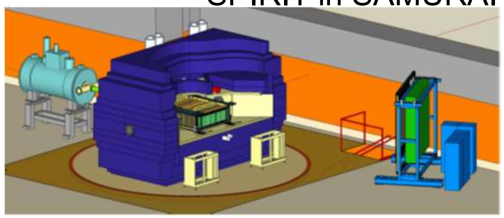
FOPI/SIS18

HADES/SIS18

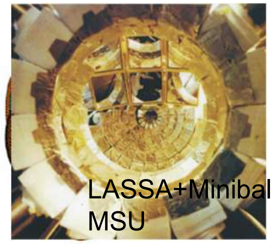


INDRA/GANIL

SPIRIT in SAMURAI

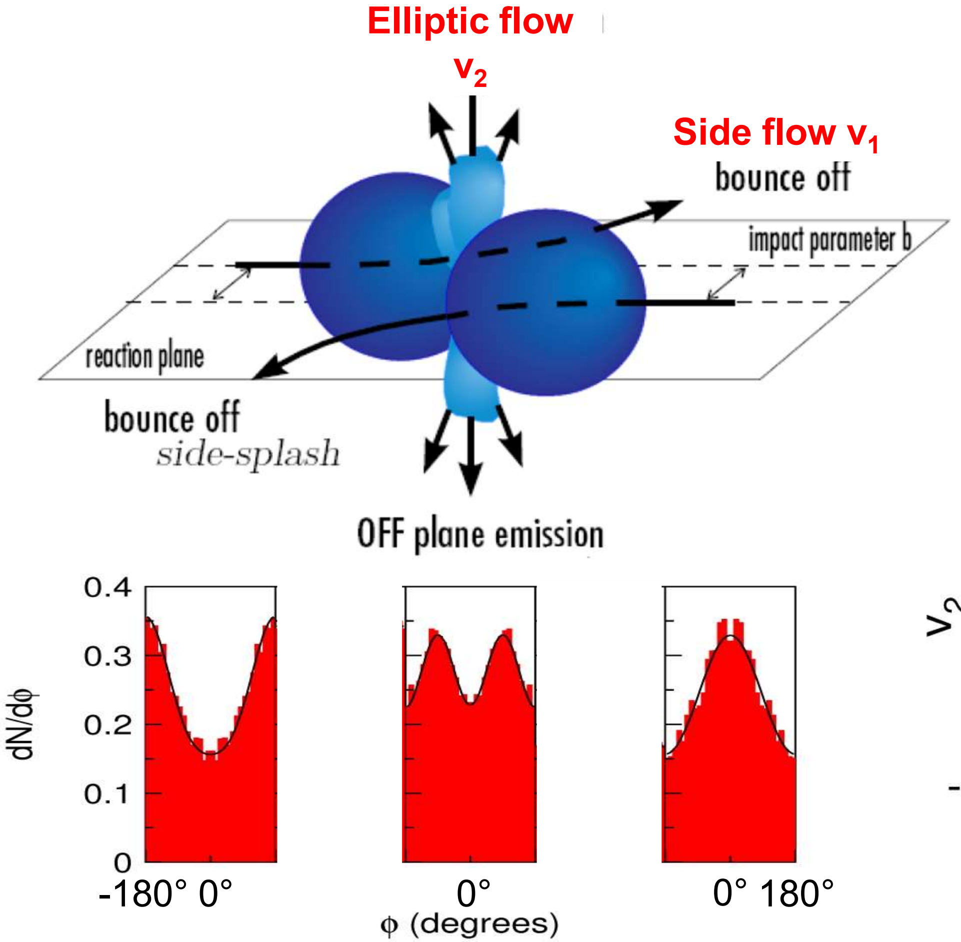


NIMROD@TAMU



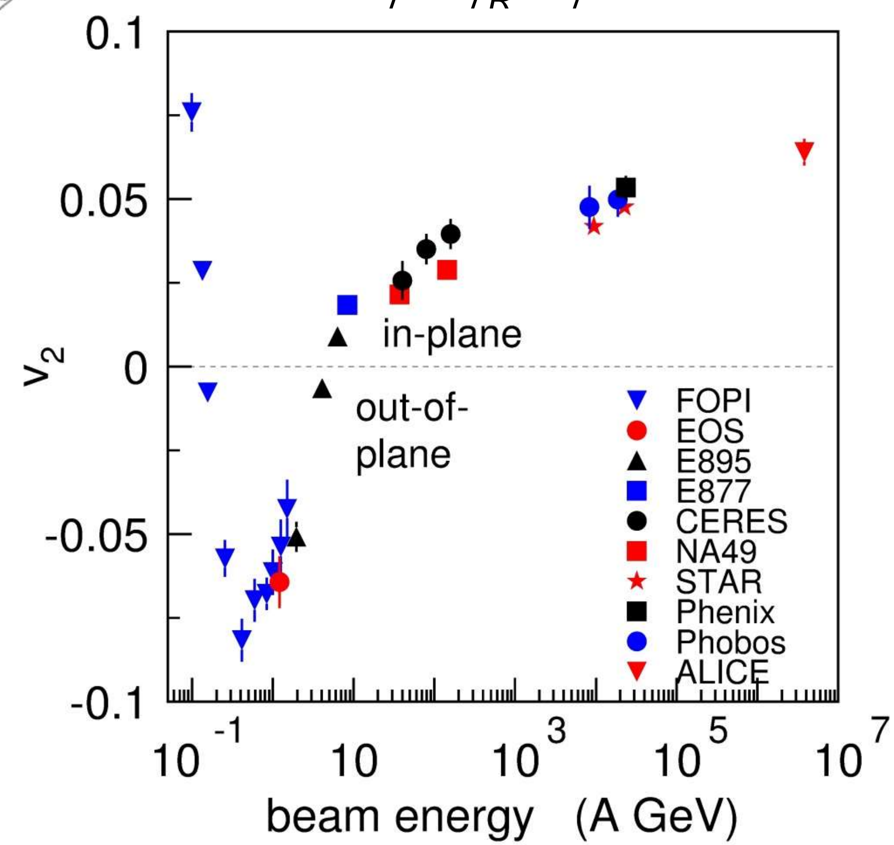
LASSA+Miniball – MSU

1. Flow



$$\frac{dN}{d\phi} \sim 1 + 2v_1\cos(\phi) + 2v_2\cos(2\phi)$$

$$\phi = \phi_R - \varphi$$

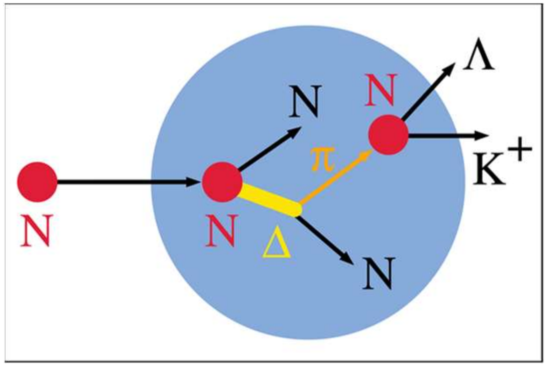


Discovery at Bevalac

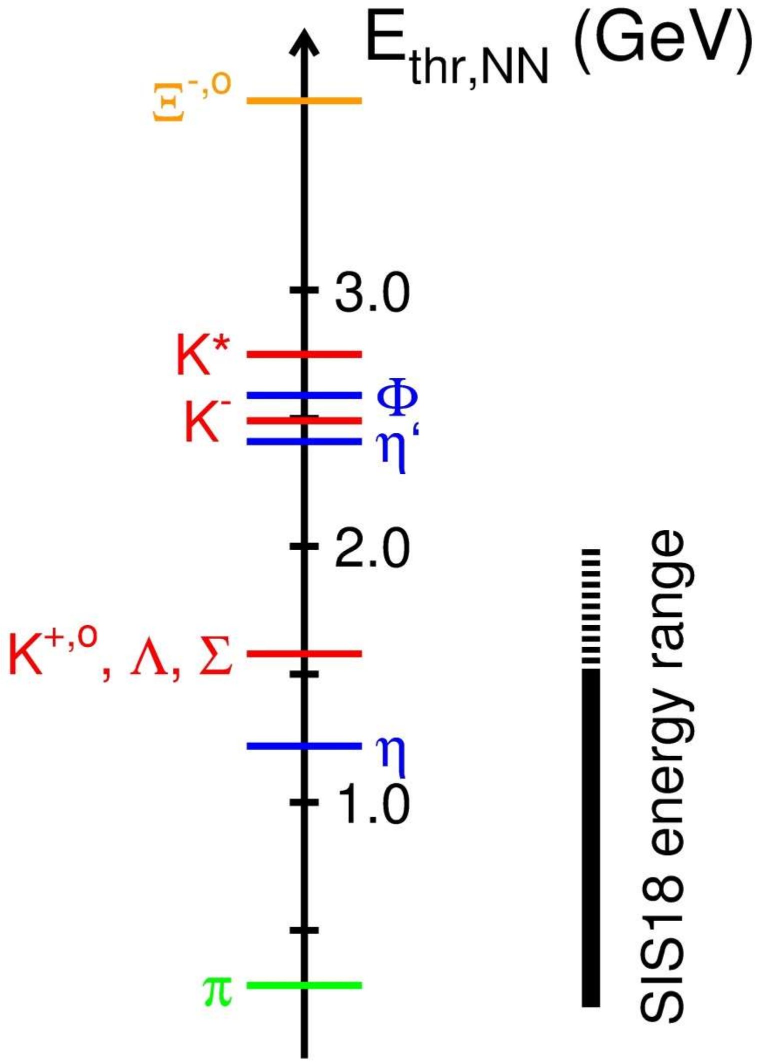
H.A. Gustafsson, et al., Phys. Rev. Lett. 52 (1984) 1590.
R.E. Renfordt, et al., Phys. Rev. Lett. 53 (1984) 763.

2. Particle production

Possible at energies below to the threshold in NN system



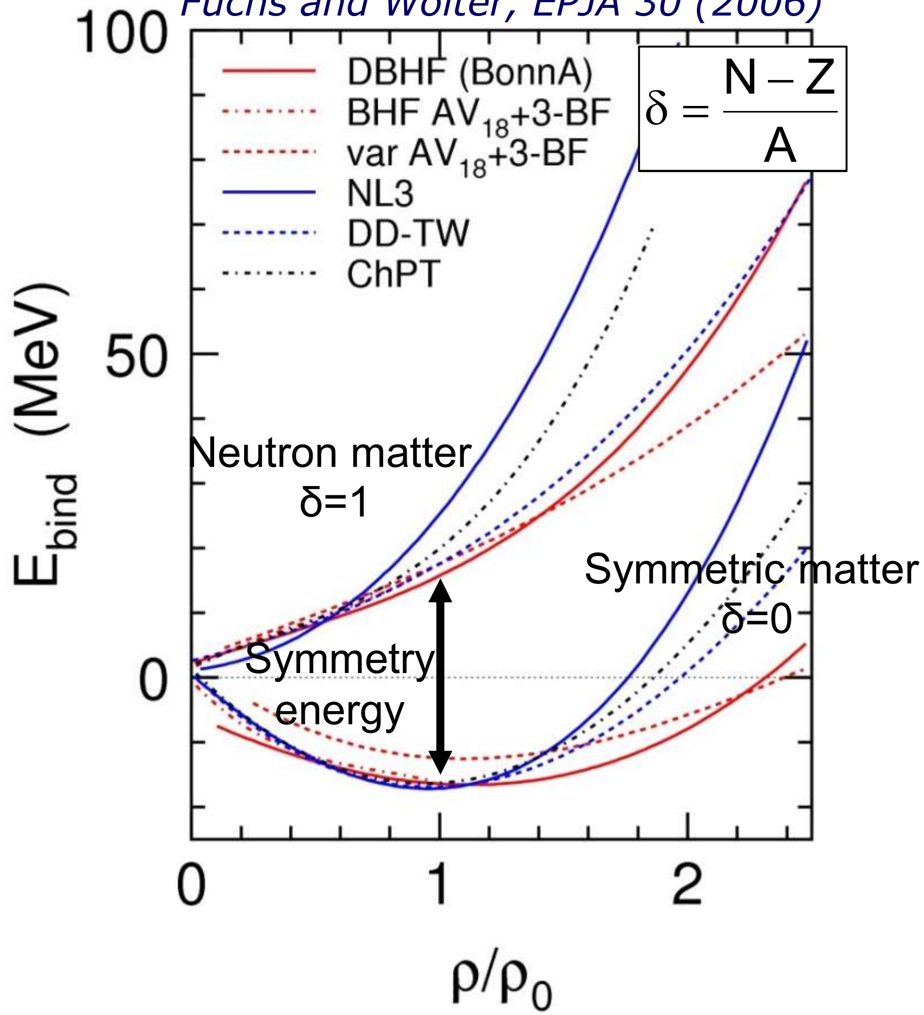
- multi-step processes can cumulate the energy needed
- intermediate resonances used as an energy reservoir
- production at high densities due to short life time of resonances
- probing density (number of binary collisisons)



Interpretation of results

- heavy ion reactions rapidly evolving, transient state
- influenced by
  - **nuclear matter equation of state**
    - *momentum dependence*
  - in-medium cross sections
    - *Pauli blocking*
  - in-medium characteristics of particles
    - *effective masses/potentials, spectral functions*
    - *decay widths*
- microscopic transport models needed
- convincing conclusions on basic nuclear properties imply a successful simulation:
  - of the full set of experimental observables
  - with the same code
  - using the same physical and technical parameters.

Fuchs and Wolter, EPJA 30 (2006)

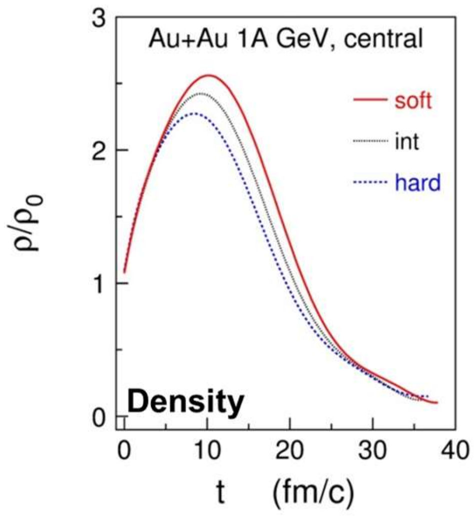


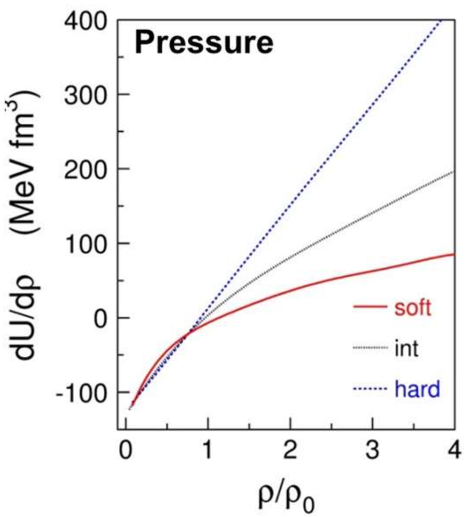
EQUATION OF STATE OF SYMMETRIC MATTER

Equation of state for symmetric nuclear matter

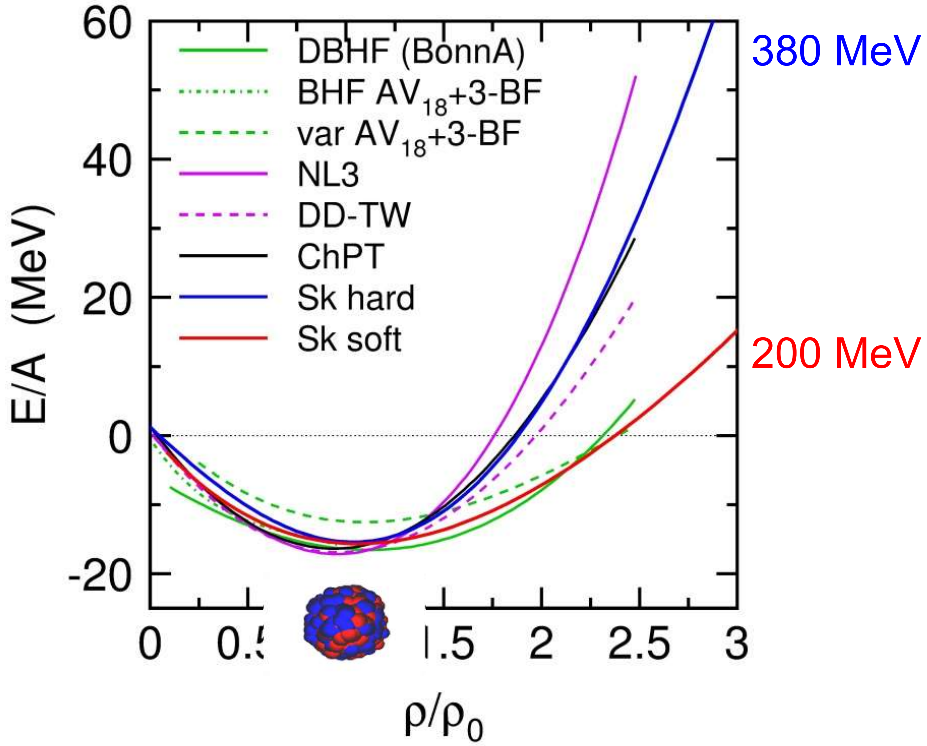
- infinite symmetric nuclear matter N=Z
- ground state properties: ρ_0 = 0.16 N/fm^3 and $E(\rho_0)$ = -16 MeV
- expansion in density:

$$E(\rho, T=0, \delta=0) = E_0 + \frac{K}{18\rho^2}(\rho-\rho_0)^2 + \ldots$$





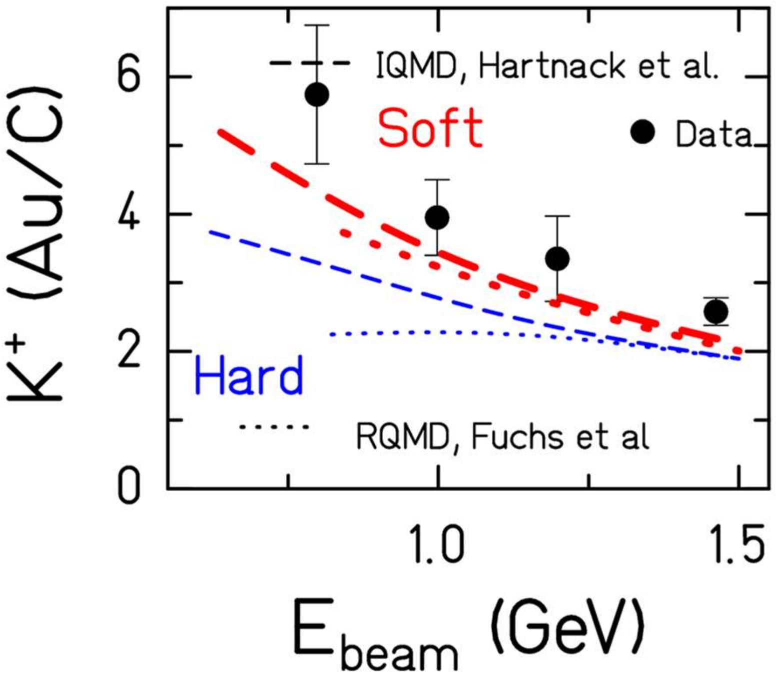
Fuchs and Wolter, EPJA 30 (2006)

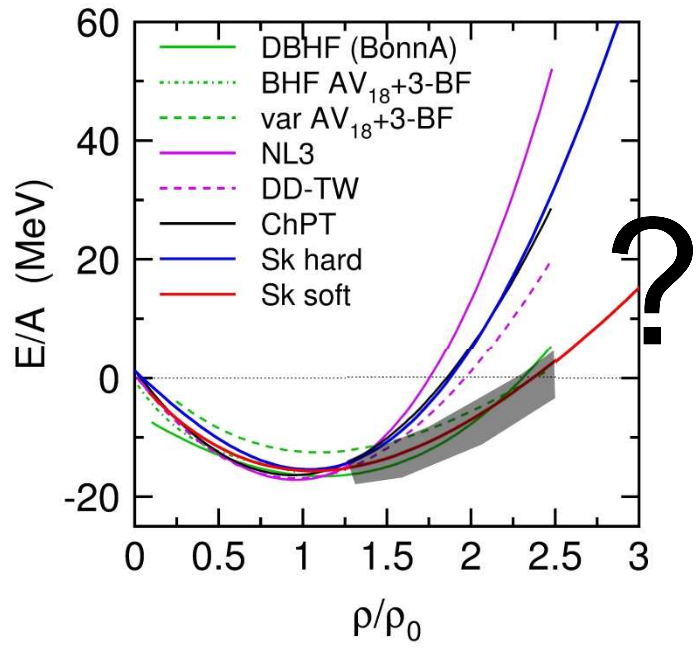


J. Piekarewicz, PRC 69 (04) 041301,
RMF: K=248 MeV
G. Colò et al.,PRC 70 (04) 024307
Skyrme HF: K=230 MeV
S. Shlomo et al. Eur. Phys. J. A 30, 23 (06)
K=240±20 MeV
D.H. Youngblood et al., PRC 80, 064318 (09):
K=231±5 MeV

Compressibility of symmetric nuclear matter: Kaon production

C. Sturm et al., PRL 86 (01) 39
Ch. Hartnack et al., PRL 96 (2006) 012302

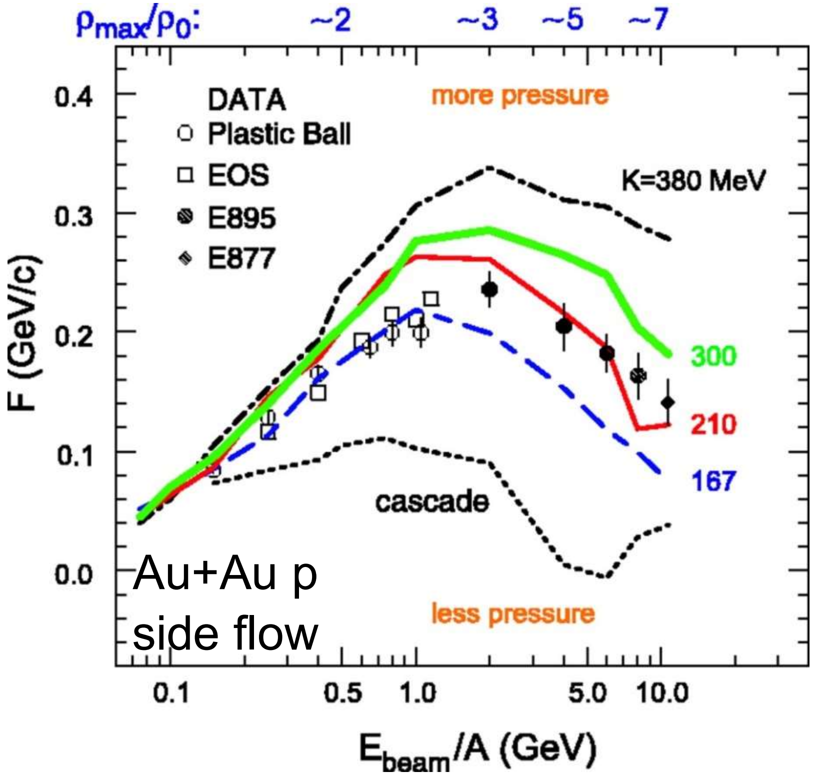


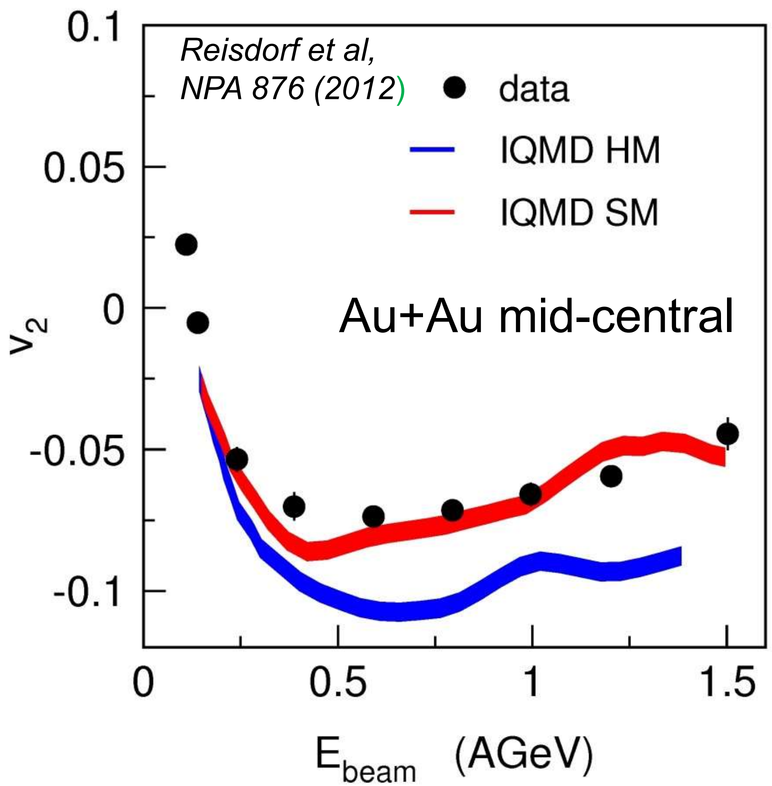


- Kaon yield
  ~ density reached
  ~ compressibility
- robust observable
  - independent on model ingredients

- sensitivity to compressibilty largest below threshold
- relevant density ~2ρ_0

Flow sensitive to pressure built up during reaction

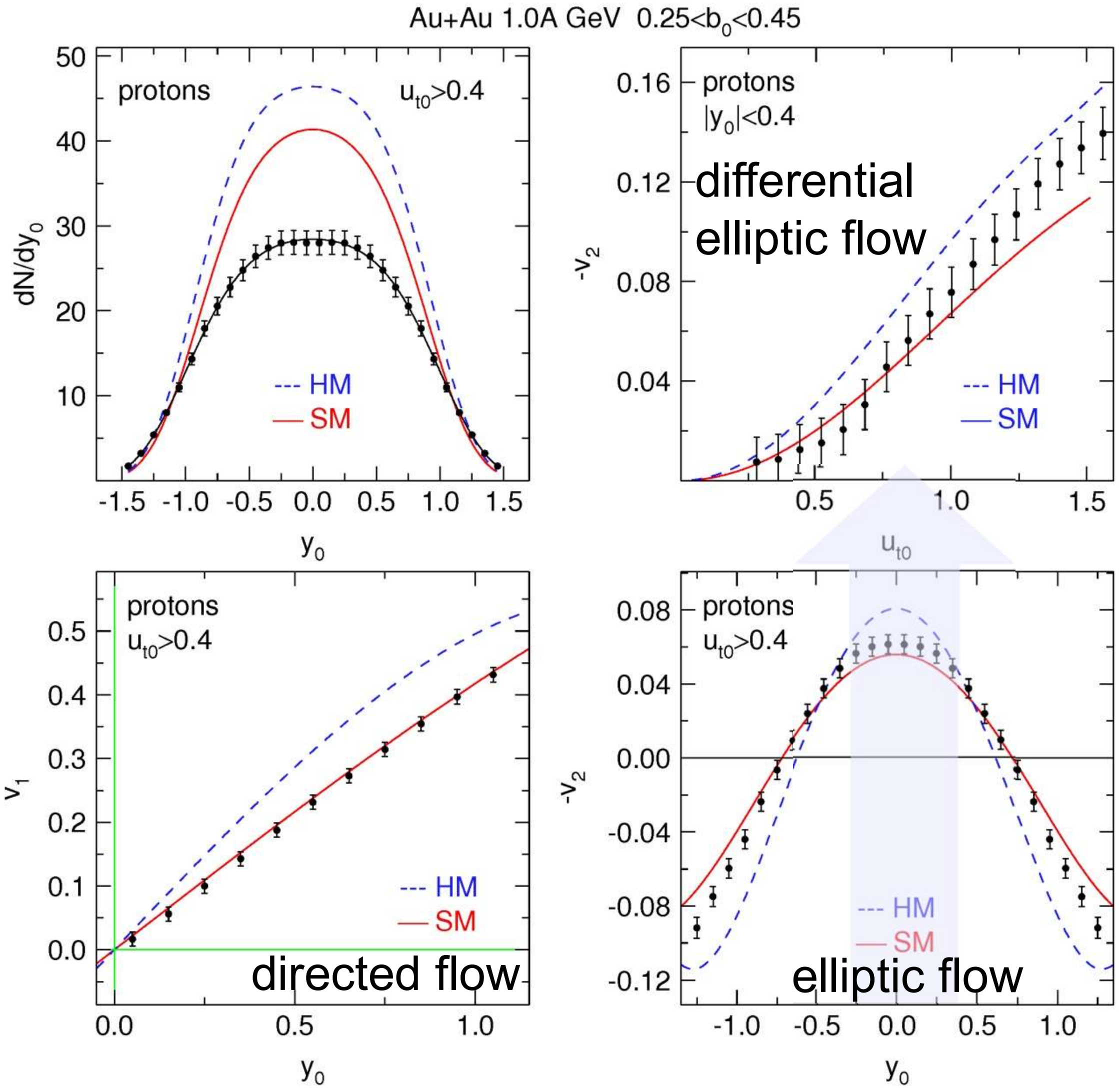




- "*additional constraints needed on momentum dependence of NN potential and in-medium cross sections*"
- newer (FOPI) data on elliptic flow in agreement with a soft EOS (SM)

→ available heavy ion reaction (FOPI) data in this energy regime including Kaon production is reasonably described by this model (input parameters constrained with experimental data)

Collective flows in Au+Au at 1.0A GeV



W. Reisdorf et al, Nucl. Phys. A 876 (2012) 1

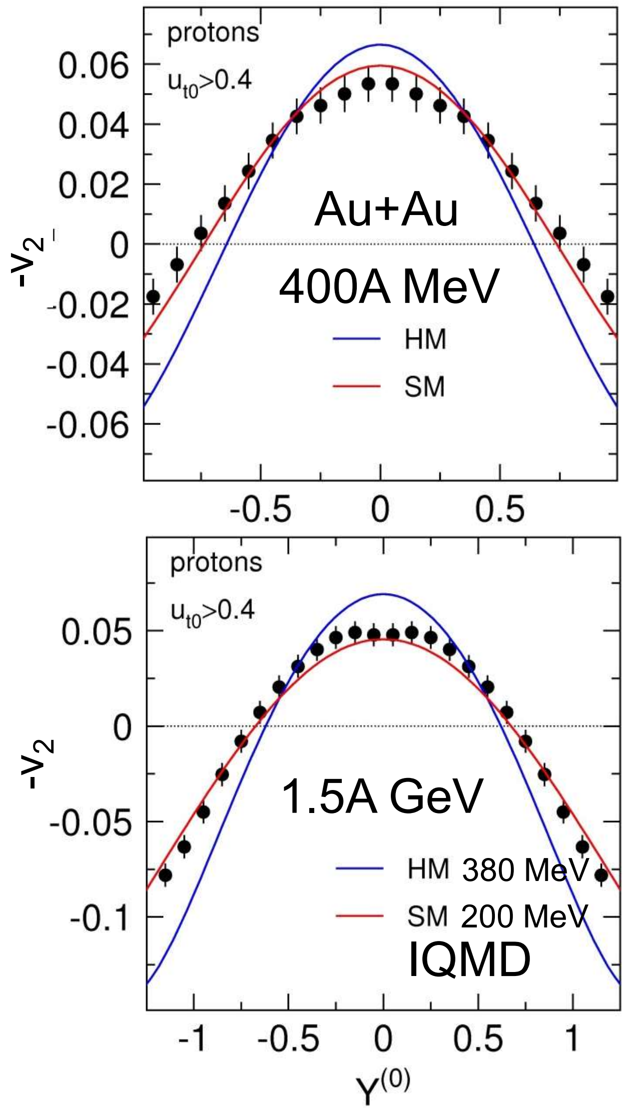
All flow results

- Au+Au 0.4 – 1.5AGeV Ru+Ru/Zr+Zr
- directed flow
- elliptic flow
- protons
- d, t, ^{3}He, α

reasonably well described by IQMD transport code employing **a soft EOS for symmetric matter**

IQMD, C. Hartnack et al. EPJ A1 (1997) 151

Elliptic flow at energies 0.25-1.5 AGeV

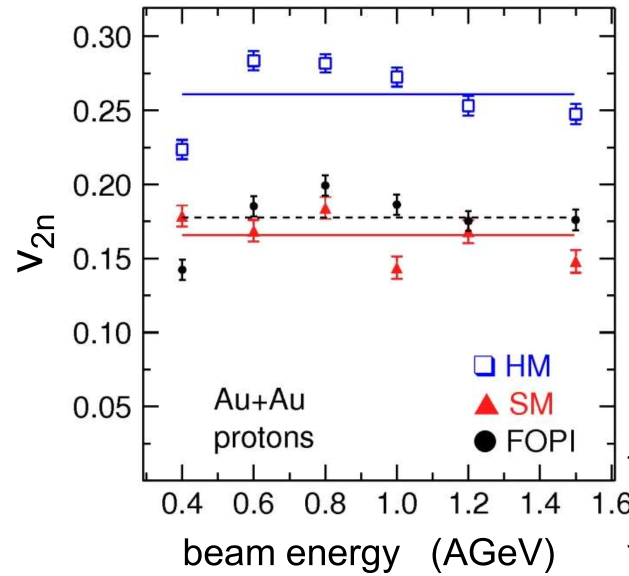


W. Reisdorf et al, Nucl. Phys. A 876 (2012) 1

Parametrization of shape:

$$v_2(Y^{(0)}) = v_{20} + v_{22} \cdot Y^{(0)2}$$

$$v_{2n} = |v_{20}| + |v_{22}|$$

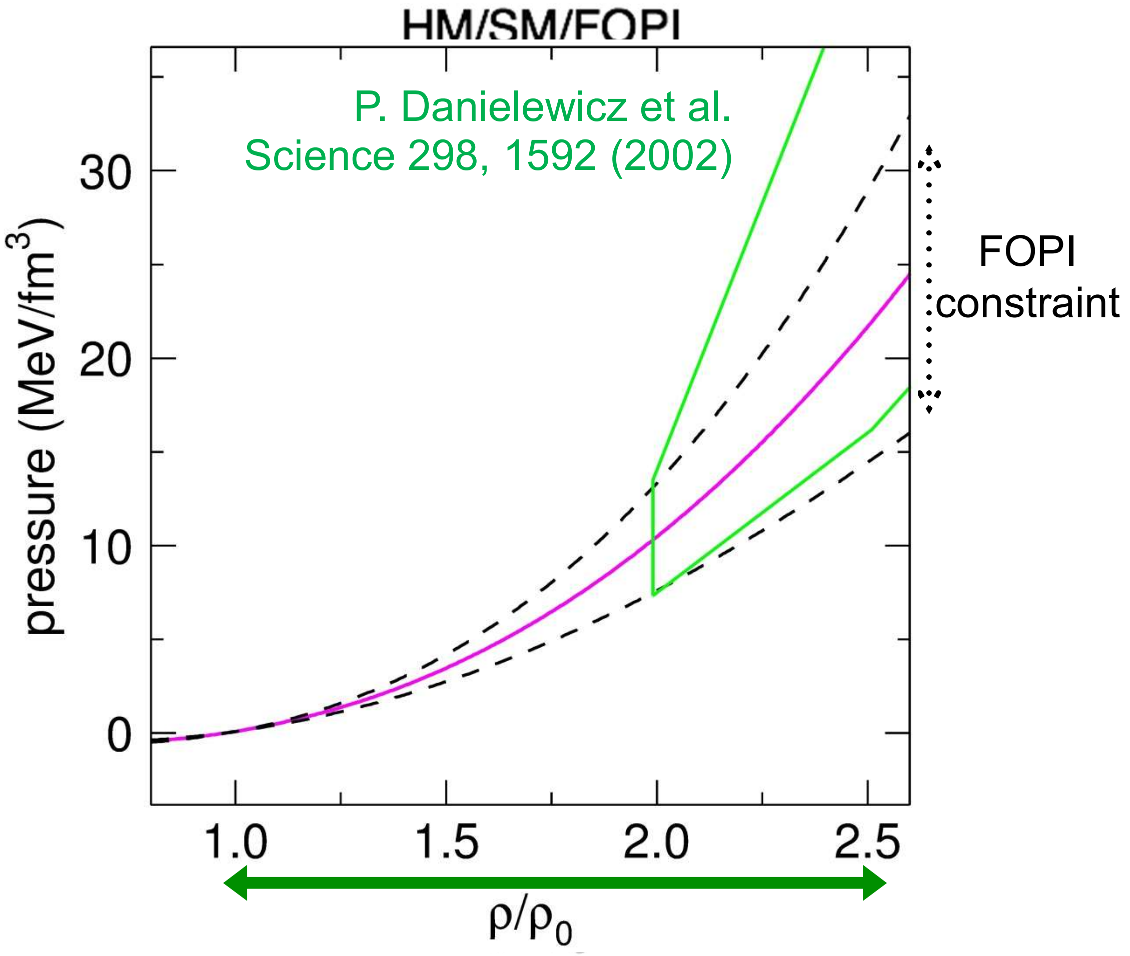


A. LeFevre et al NPA 945, 112 (2016)

- sensitive to EOS over a large energy range
- $v_{2n}(E_{beam})$ varies by a factor ≈1.6 >> measured uncertainty (≈1.1)
- relevant density range $\rho \simeq (1-3)\,\rho_0$
- extracted compressibility K=190±30 MeV

Resulting constraint

- phenomenological EOS
  HM and SM include the saturation point at $\rho/\rho_0 = 1$,
  E/A = −16 MeV by construction,
  fixes the absolute position of the curves:
- the heavy ion data are only sensitive to the shape, i.e. the pressure (derivative).
- a stiff EOS, characterized by K_0 = 380 MeV is not in agreement with flow data in the incident energy range 0.4 - 1.5 A.GeV.



A. LeFevre et al NPA 945, 112 (2016)

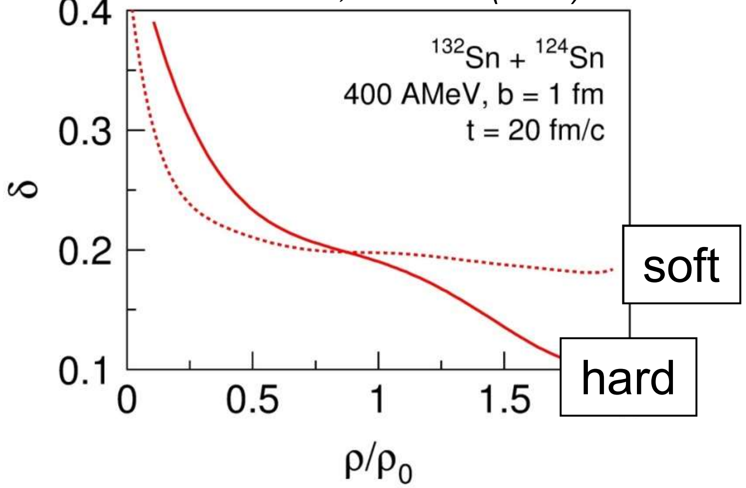
SYMMETRY ENERGY

Symmetry energy

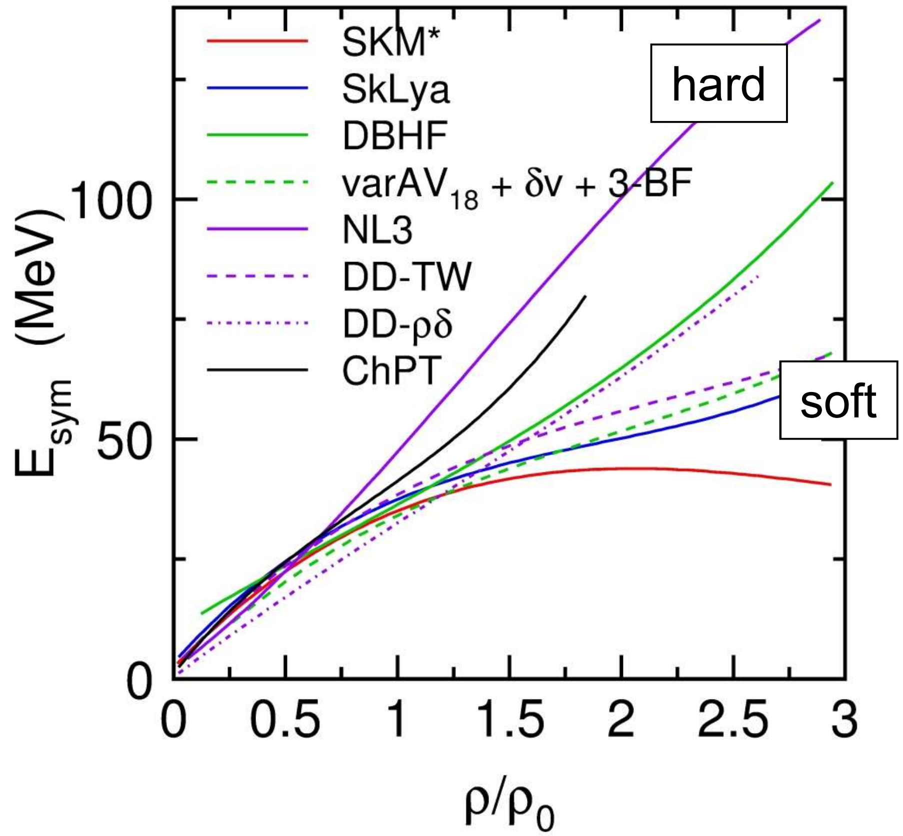
$$E_{sym}(\rho) = E_{sym,0} + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2 + \ldots$$

Largely unconstrained at high densities → related to uncertainty of three-body and tensor forces at high density

Bao-An Li, NPA 708 (2002)



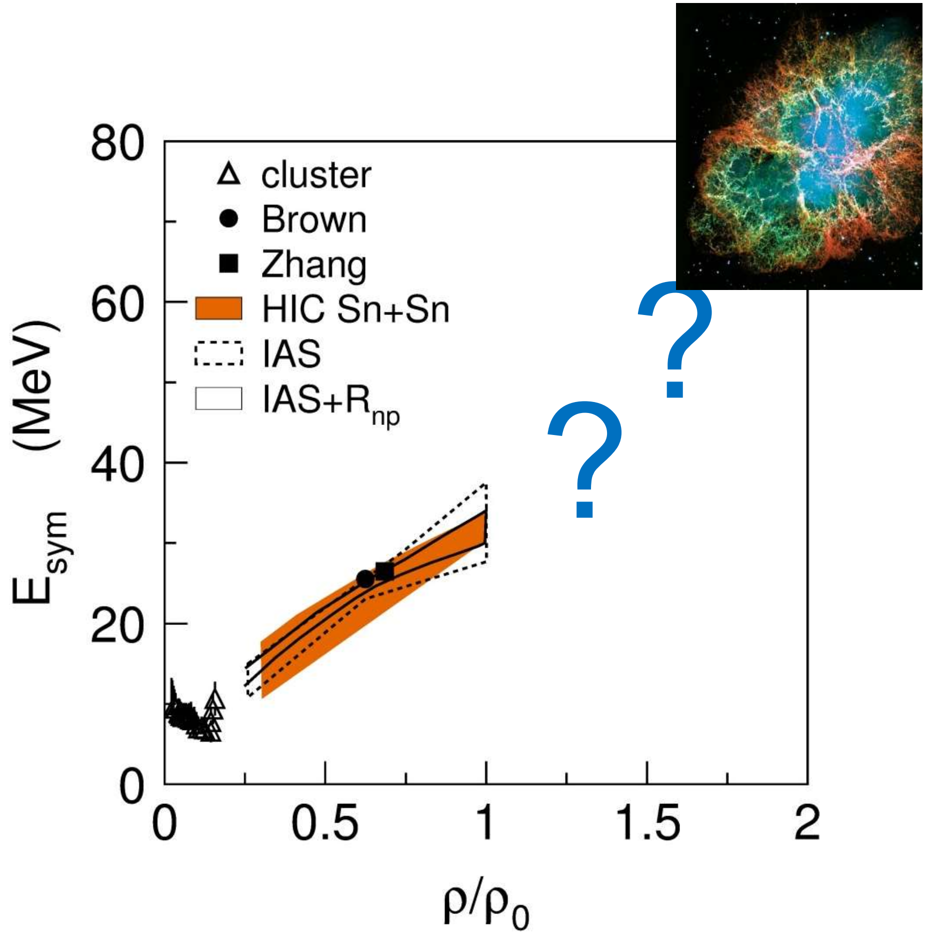
Fuchs and Wolter, EPJA 30 (2006)



Symmetry energy

Sensitive observables that are or will be more extensively explored :

- neutron stars...
- masses
  - Isobaric Analog States (IAS)
- neutron skins
  - scattering with electrons, anti-protons
  - excitation of nuclei: Pygmy resonances, dipole polarizability...
  - neutron removal cross section
- cluster formation at low densities
- fragmentation of nuclei
- isospin diffusion und isospin drift between nuclei of different N/Z in peripheral HIC
- neutron/proton, t/^{3}He spectra and collective flows
- π-/π+ multiplicities and spectra



cluster/HIC Sn+Sn/ IAS:
Horrowitz et al. JPhG 41 (2014)
Brown: arXiv:1308.3664

Symmetry energy at supra-normal densities

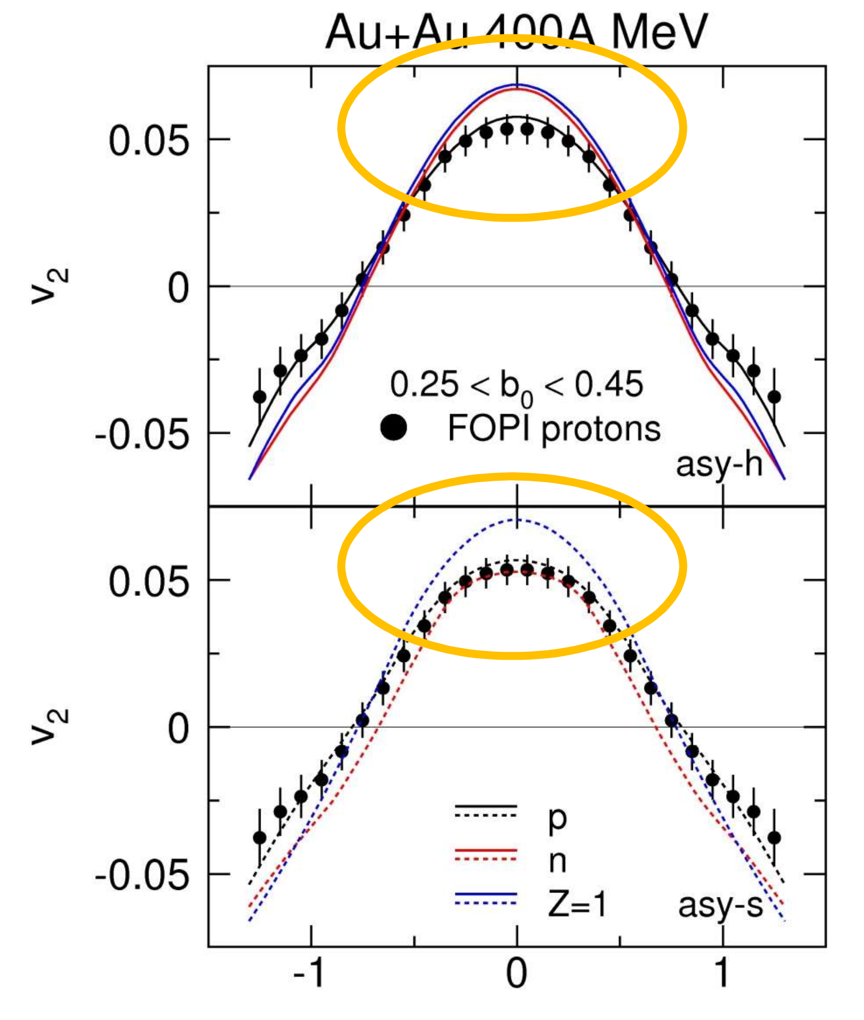
Differential elliptic flow v_2 of n/p
UrQMD* (Q. Li et al.) predicts

"hard" E_{sym} → "soft" E_{sym}	protons unchanged neutron and proton flow inverted

Towards model invariance:
tested stability with different models:

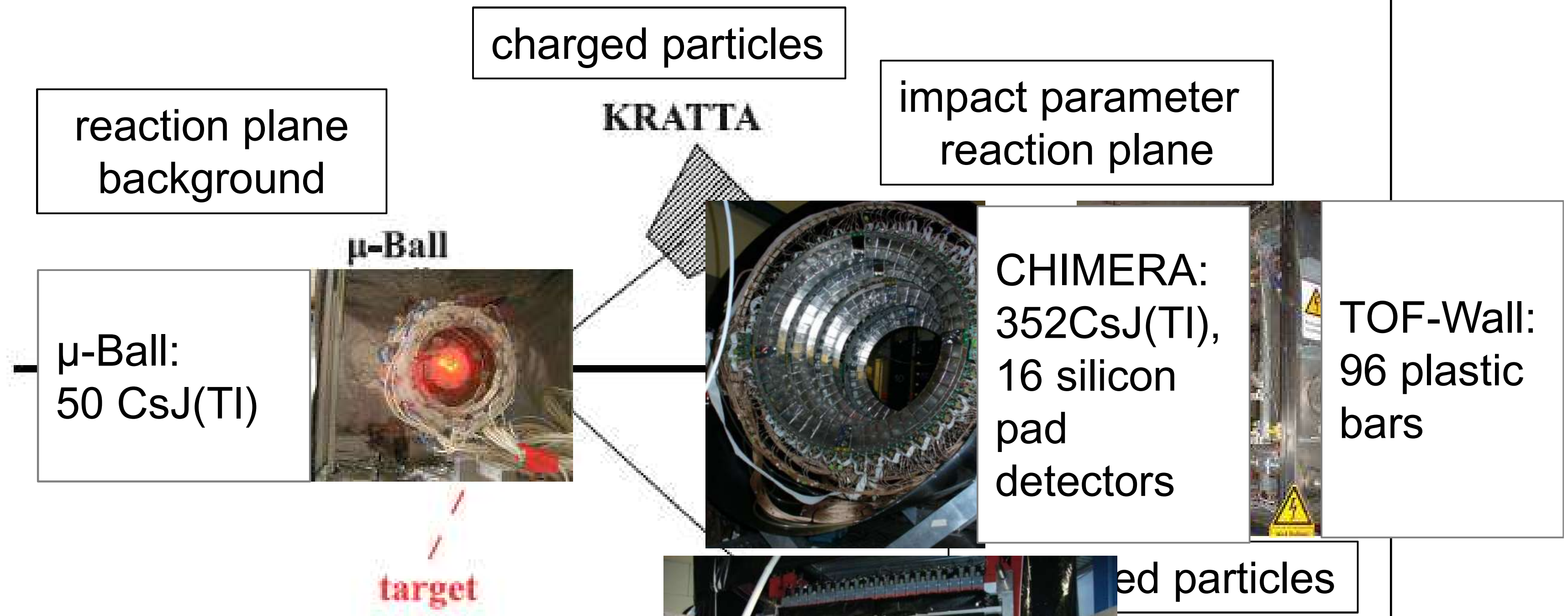
- soft vs. hard EOS **190<K<280 MeV**
- density dependence of $\sigma_{NN,elastic}$
- asymmetry dependence of $\sigma_{NN,elastic}$
- optical potential
- momentum dependence of isovector potential

M.D. Cozma et al., arXiv:1305.5417
P. Russotto et al., PLB 267 (2010)
Y. Wang et al.,PRC 89, 044603 (2014)

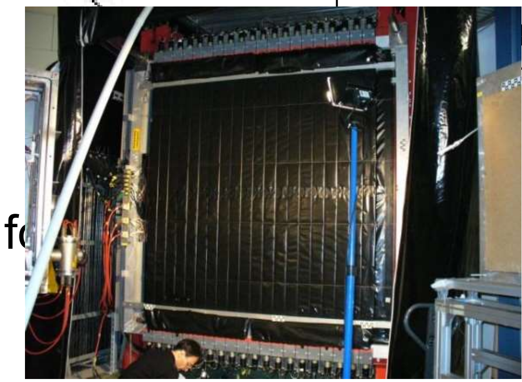


UrQMD*: Qingfeng Li
Data. W. Reisdorf et al.

ASY – EOS Experiment

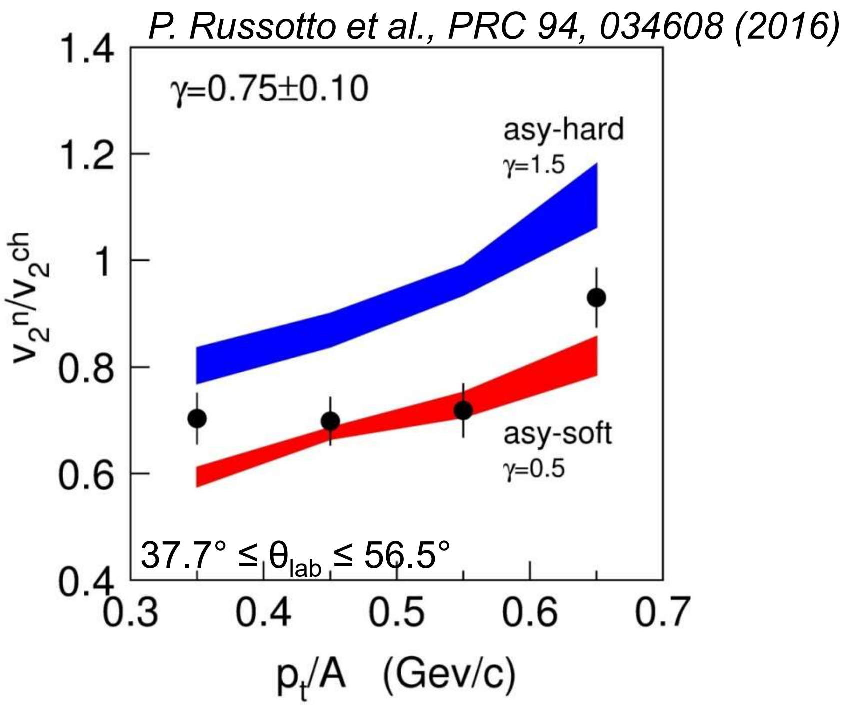


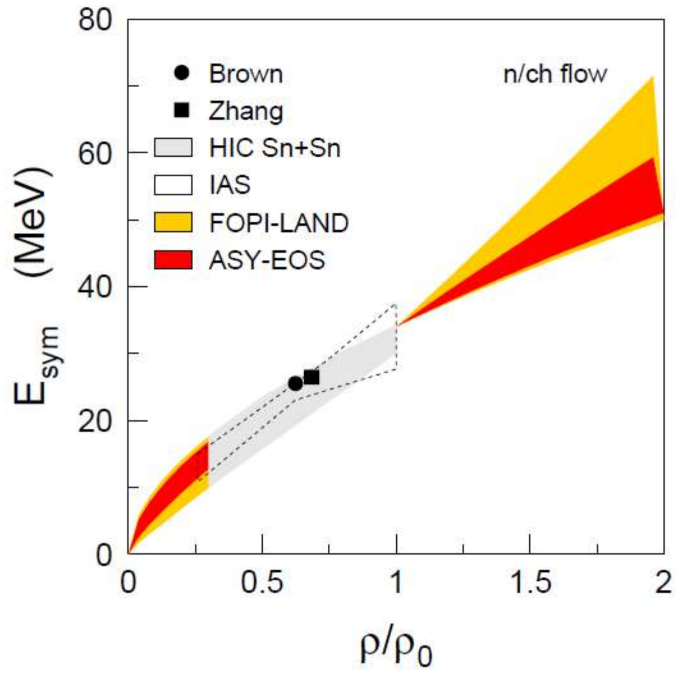
ASY-EOS



- background measurements f
  neutrons (shadow bars)
- 400A MeV Au+Au at GSI

Elliptic flow ratio of neutrons and charged particles



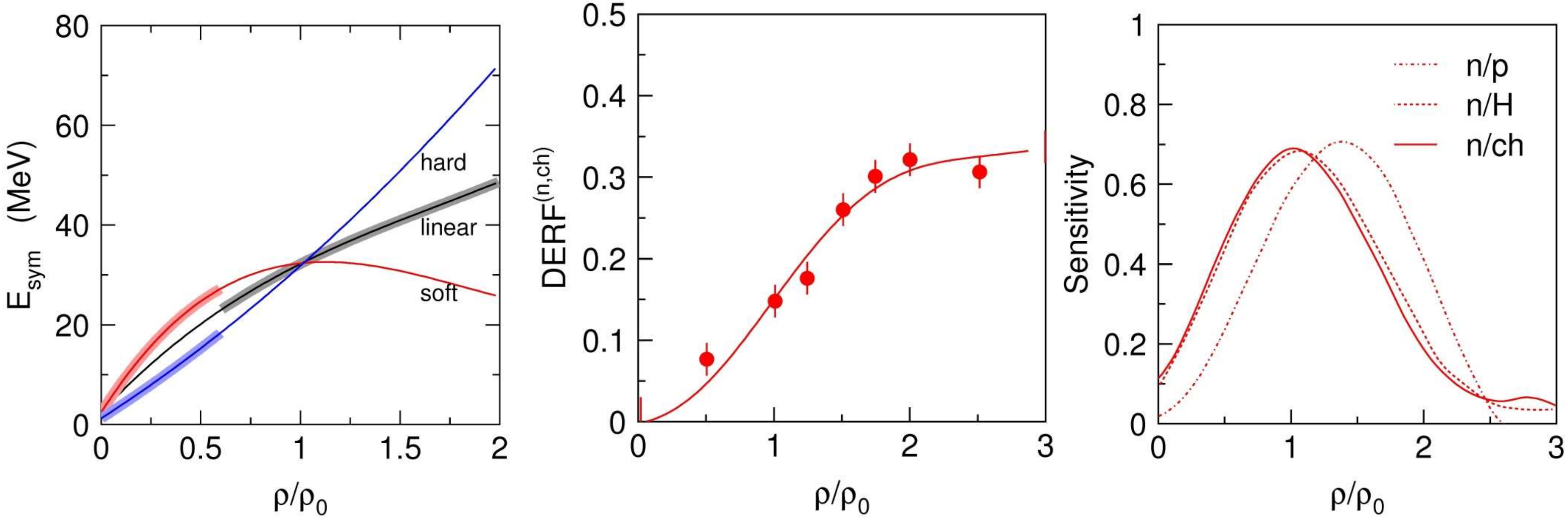


- parametrization for SE used in UrQMD* model:

$$E_{sym} = E_{sym}^{pot} + E_{sym}^{kin} = 22\text{MeV}\cdot(\rho/\rho_0)^{\gamma} + 12\text{MeV}\cdot(\rho/\rho_0)^{2/3}$$

- systematic errors corrected: $\gamma = 0.72 \pm 0.19$
- slope parameter: $L = 72 \pm 13$ MeV, $E_{sym}(\rho_0) = 34$ MeV
- slope parameter: $L = 63 \pm 11$ MeV, $E_{sym}(\rho_0) = 31$ MeV

Extracting relevant density range



P. Russotto et al., PRC (2017)

- deducing density where the difference between neutron and charged particle flow is originating from by using transport models

$$\mathrm{DERF}^{(n,Y)}(\rho) = \frac{v_2^n}{v_2^Y}(\mathrm{hard},\rho) - \frac{v_2^n}{v_2^Y}(\mathrm{soft},\rho)$$

- DERF: difference in elliptic flow ratios for two different S(ρ)
  - at large ρ full splitting
  - sensitivity is given by the derivative of DERF

Pion production as probe

- symmetry energy influences n/p ratio → nn, np, pp collisions

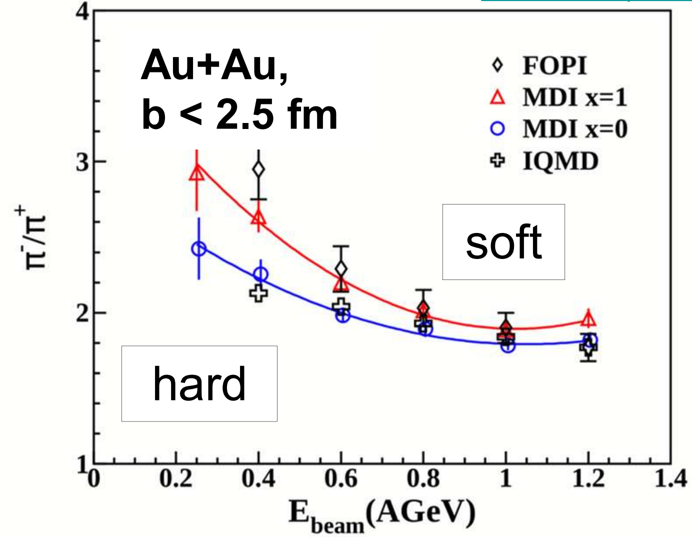
hard SE $\frac{n}{p}\downarrow \Rightarrow \frac{Y(\Delta^{0,-})}{Y(\Delta^{+,++})}\downarrow \Rightarrow \frac{\pi^-}{\pi^+}\downarrow$

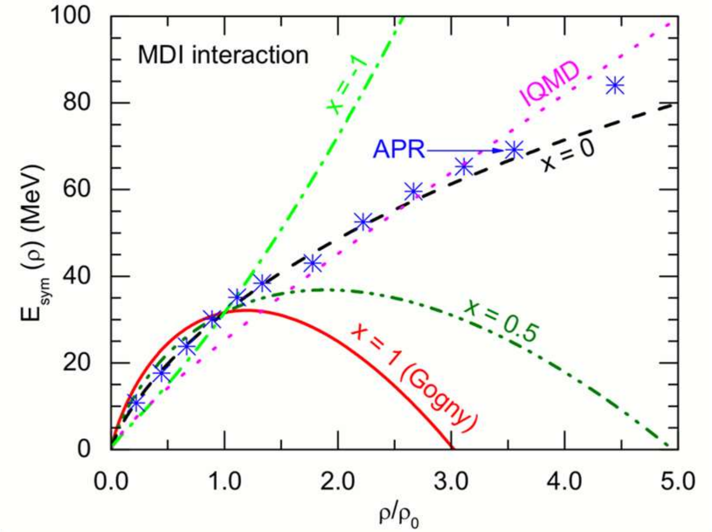
- But in the nuclear medium
  - pion optical potential, self energies, different for π^- and π^+
  - production via Δ resonances, potential
  - s- vs p-wave production
- π^-/π^+ ratio: interpretation model dependent

hard SE $\Rightarrow \frac{\pi^-}{\pi^+}$?

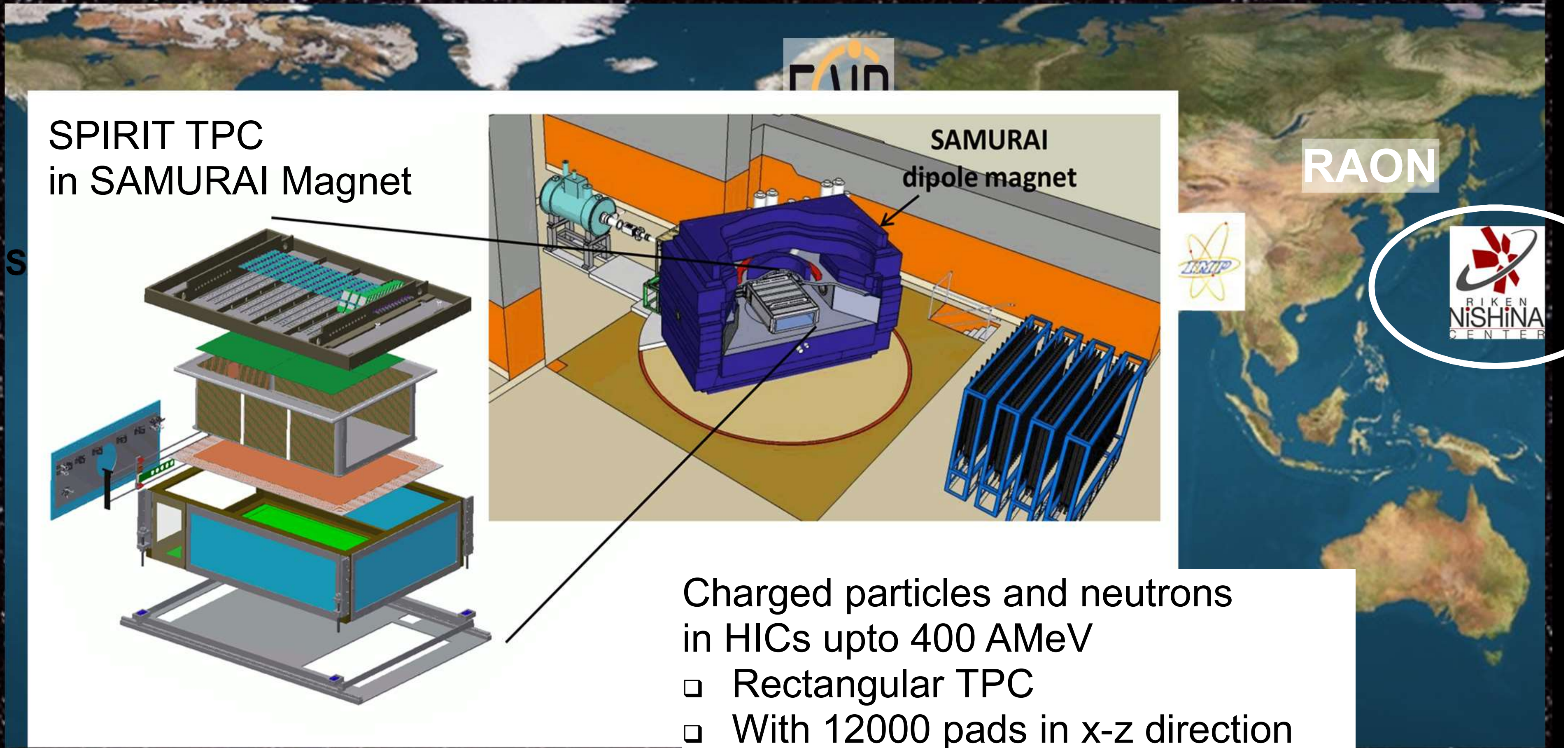
- measure double ratio $(\pi^-/\pi^+)^{n\text{-rich}}/(\pi^-/\pi^+)^{p\text{-rich}}$ $^{132}Sn+^{124}Sn$ / $^{108}Sn+^{112}Sn$

Data: W. Reisdorf et al., NPA 781 (2007)
Calculations: *Z. Xiao et al, PRL 102, (2009)*





Measuring pion production with radioactive beams



Charged particles and neutrons in HICs upto 400 AMeV

- Rectangular TPC
- With 12000 pads in x-z direction
- Active target option
- Inside a magnet (→ charged pions)
- Neutron detector

SYMMETRY ENERGY AT HIGHER DENSITIES

Symmetry energy at higher densities

Higher density → higher beam energy

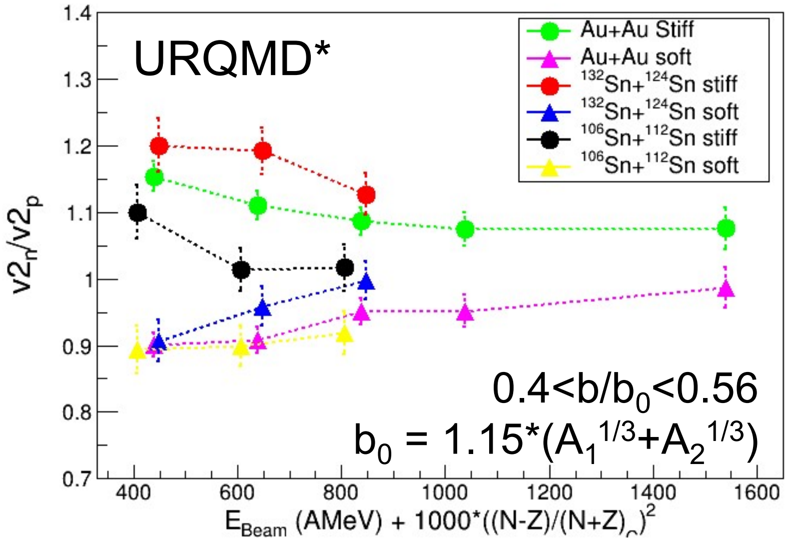
Elliptic flow ratio of n and p
Sensitivity decreasing at higher beam energies but still existing

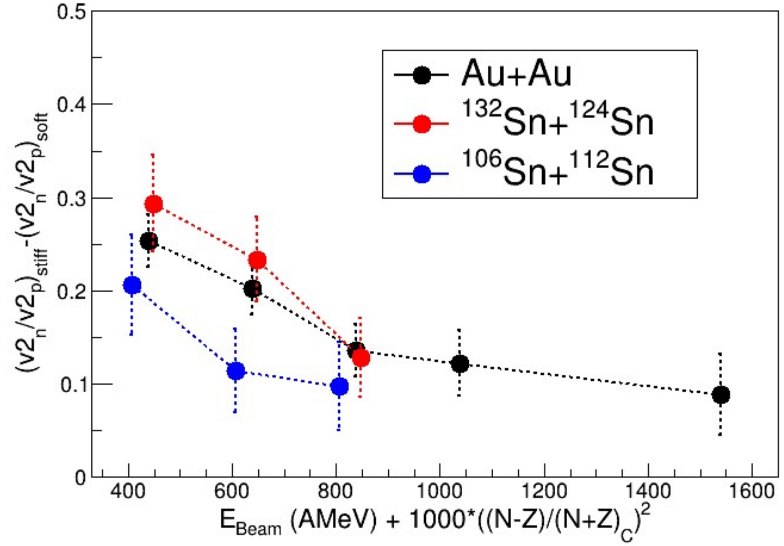
NEW ASY-EOS "proposal":
Study of

AuAu, ^{112}Sn+Sn, ^{132}Sn+Sn
400 and 900 AMeV

measure Neutrons/protons:
NeuLAND@R^{3}B
charged particles:
Kratta, Califa@R^{3}B
impact parameter vector:
FOPI Plawa , Krakow Barrel

positive response from PAC

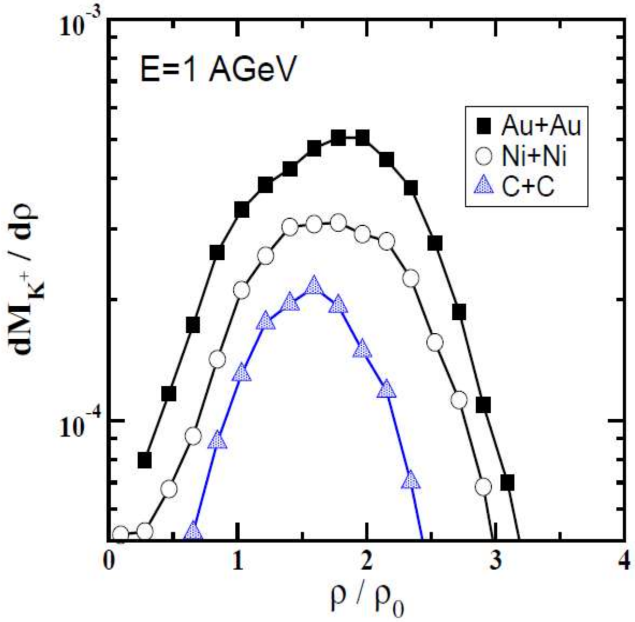




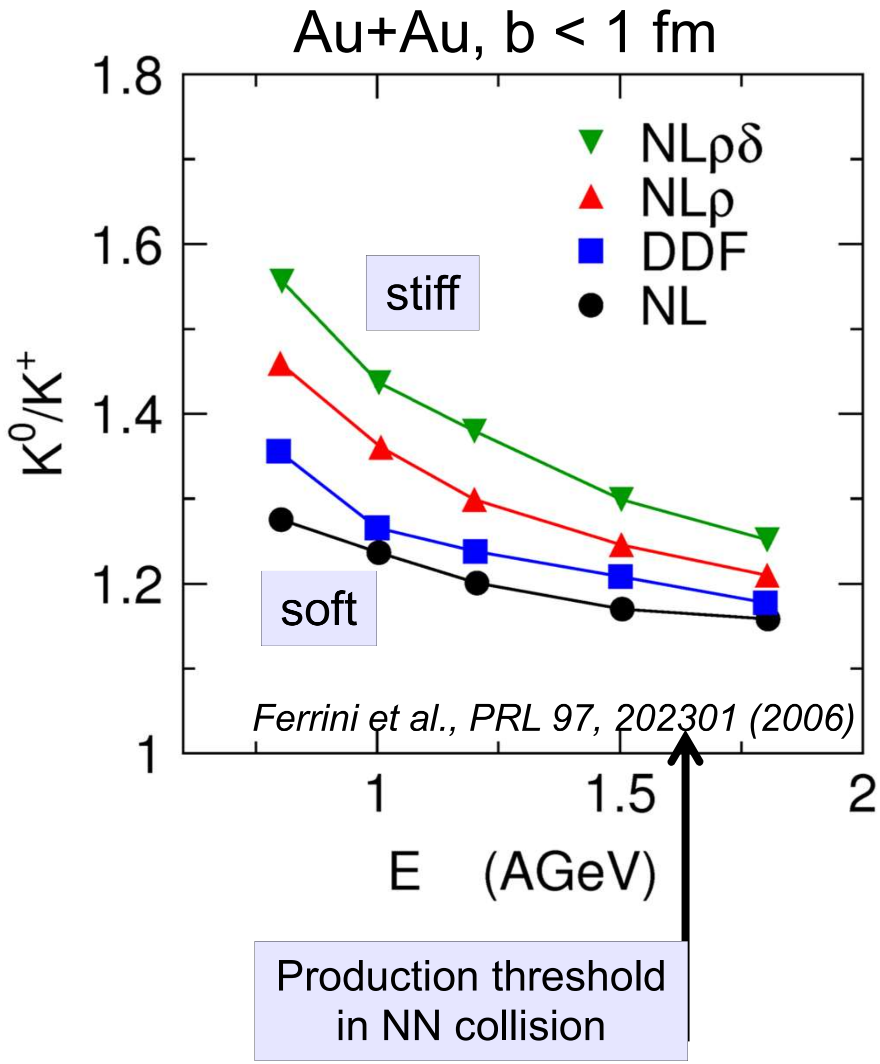
Kaon production

Kaons

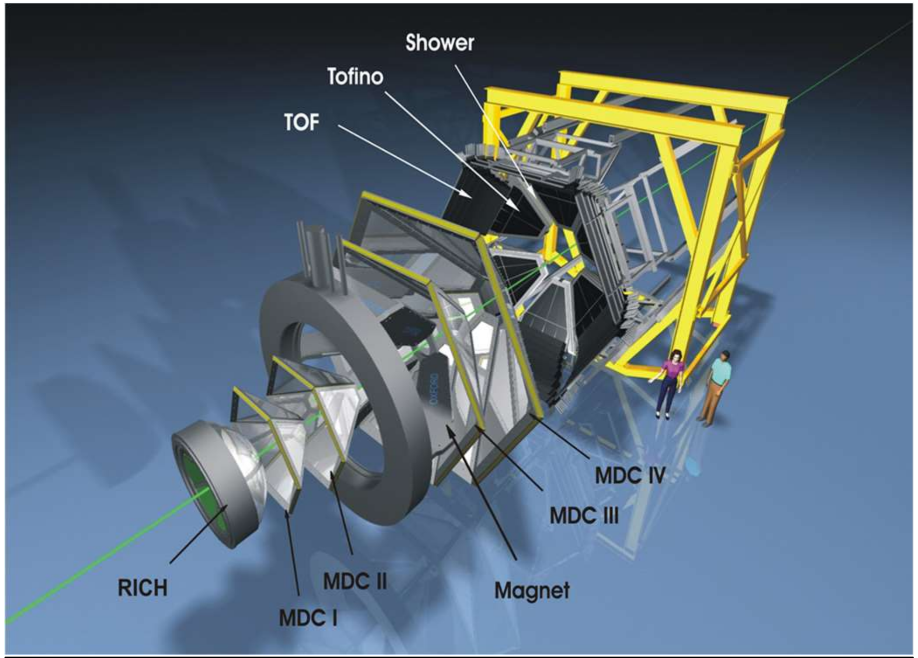
- subthreshold production is sensitive to density
- weakly interacting with medium, long mean free path
- early freeze-out
- but model dependence of pion ratio have to solved first



C. Fuchs,PR (2003)

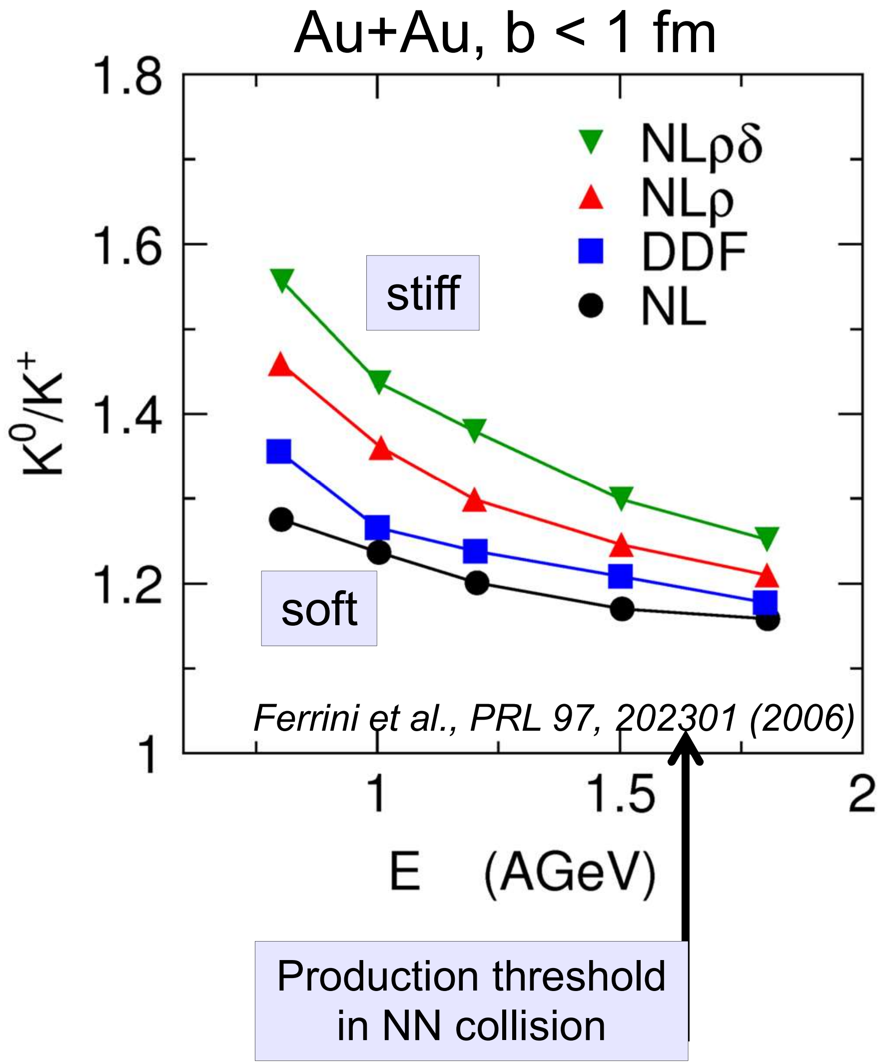


Kaon production (HADES)



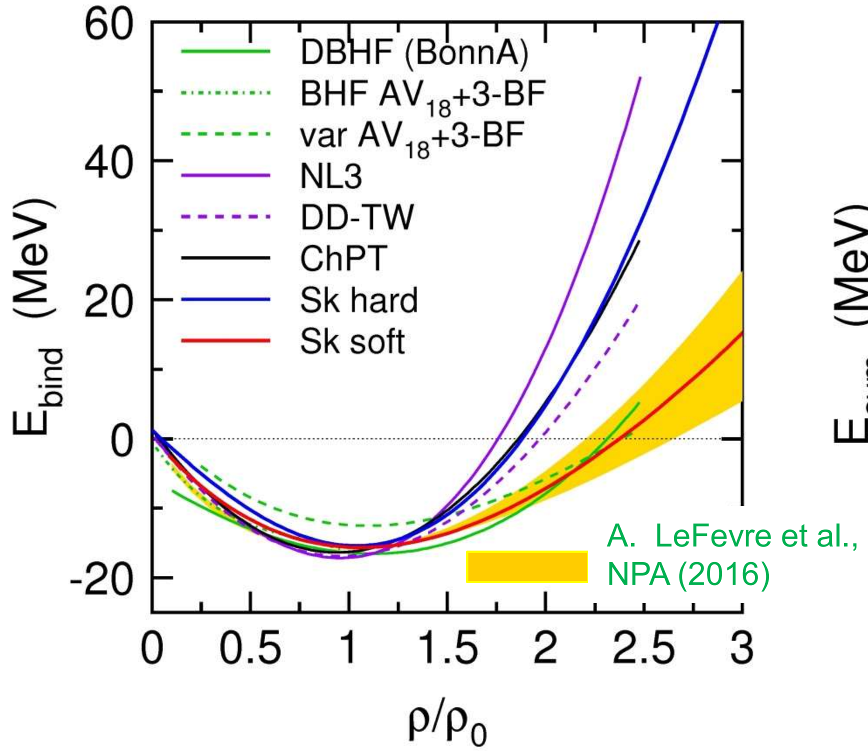
- Full azimuthal coverage, 18 to 85° in polar angle
- Hadron and lepton identification
- Event-plane reconstruction

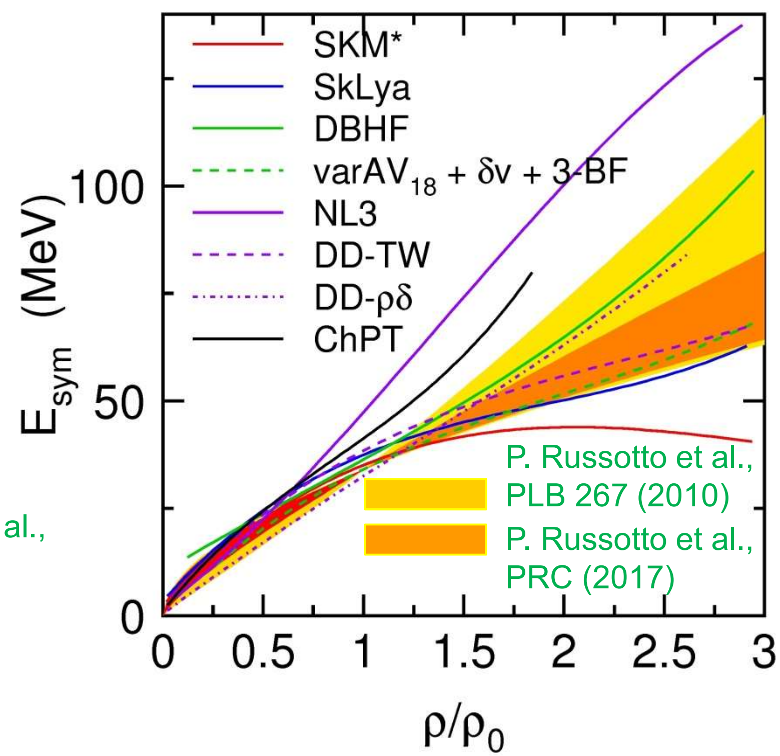
K^0/K^+ ratio at < 1 AGeV



CONCLUSION AND OUTLOOK

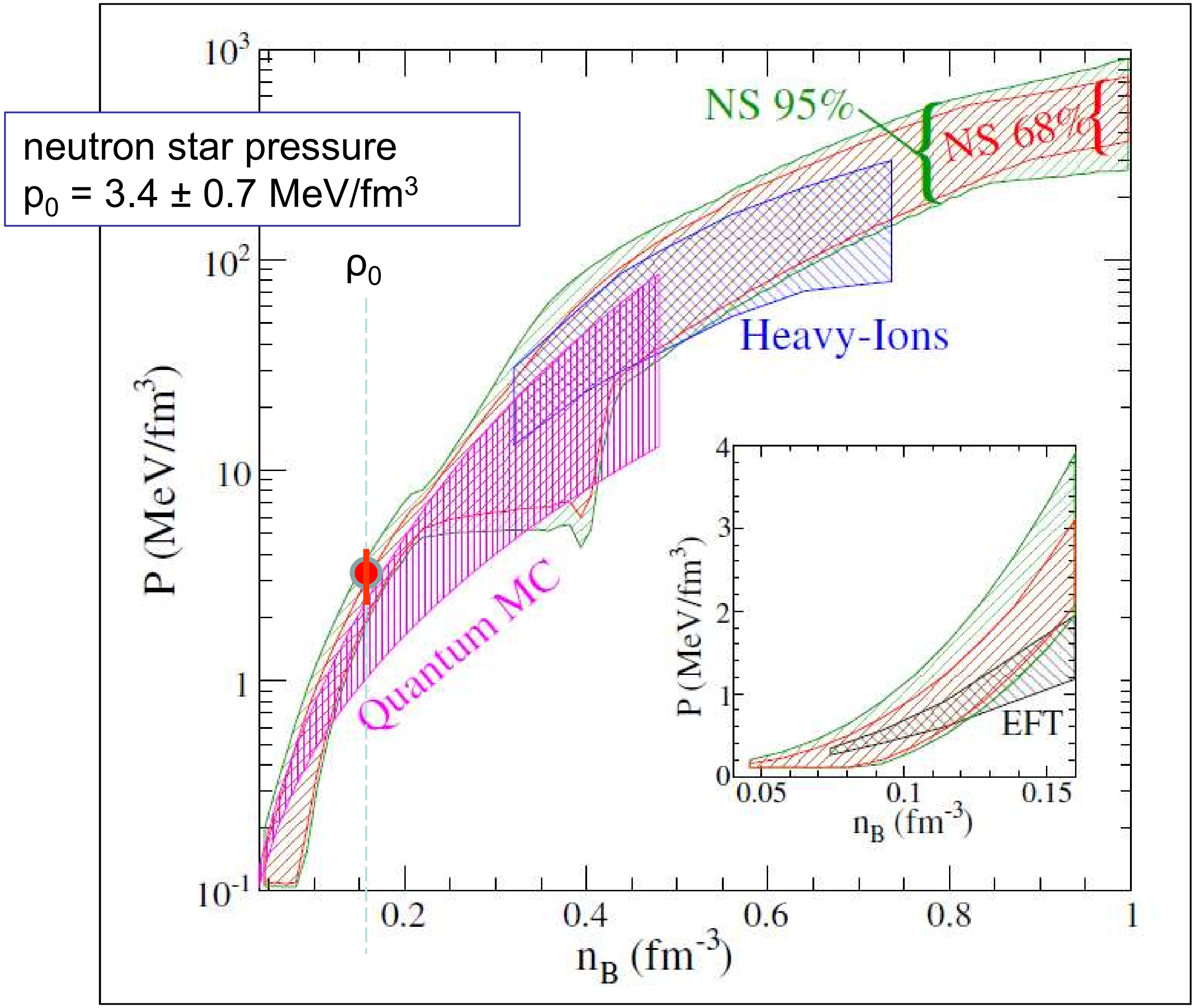
Summary





- equation of state of symmetric nuclear matter from comparison of FOPI data with IQMD
- the symmetry energy as extracted from ASY-EOS results with UrQMD*

Symmetry pressure $p_0 = 3.8 \pm 0.7$ MeV/fm^3



Steiner, Lattimer, and Brown, ApJ 765, L5 (2013)

Conclusions

- Kaon production and charged particle flow give consistent constraints on the symmetric part of the EOS
  - soft κ = MeV
  - models „benchmarked“ with existing data
- Extension to higher densities (i.e. energies needed) to improve constraints, AGS data needs extension → BM@N, CBM

- symmetry energy at intermediate densities can be constrained
- very few measurements have been done
  - n/p/ or n/charged particle flow in Au+Au
  - pion production in Au+Au
- one needs robust observable
  - largely model invariant
  - ratios or double ratios

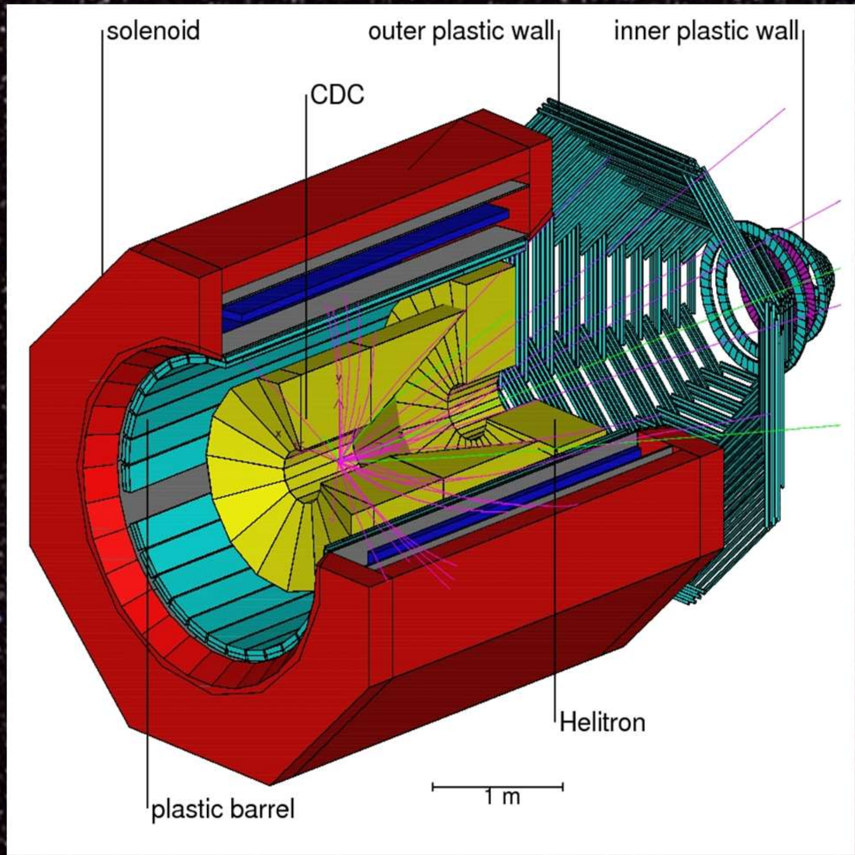
  } n/p/charged particle elliptic flow
- n/proton studies at higher energies and radioactive beams
  - ➢ submitted letter-of-intent to GSI for beam in 2019/20

- **Close collaboration between experiments and theory important**

The FOPI collaboration

A. Andronic, R. Averbeck, Z. Basrak, N. Bastid, M.L. Benabderramahne, M. Berger, P. Bühler, R. Caplar, M. Cargnelli, M. Ciobanu, P. Crochet, I. Deppner, P. Dupieux, M. Dzelalija, L. Fabbietti, J. Frühauf, F. Fu, P. Gasik, O. Hartmann, N. Herrmann, K.D. Hildenbrand, B. Hong, T.I. Kang, J. Keskemeti, Y.J. Kim, M. Kis, M. Kirejczyk, R. Münzer, P. Koczon, M. Korolija, R. Kotte, A. Lebedev, K.S. Lee, Y. Leifels, A. LeFevre, P. Loizeau, X. Lopez, M. Marquardt, J. Marton, M. Merschmeyer, M. Petrovici, K. Piasecki, F. Rami, V. Ramillien, A. Reischl, W. Reisdorf, M.S. Ryu, A. Schüttauf, Z. Seres, B. Sikora, K.S. Sim, V. Simion, K. Siwek-Wilczynska, K. Suzuki, Z. Tyminski, J. Weinert, K. Wisniewski, Z. Xiao, H.S. Xu, J.T. Yang, I. Yushmanov, V. Zimnyuk, A. Zhilin, Y. Zhang, J. Zmeskal

IPNE Bucharest, Romania, ITEP Moscow, Russia CRIP/KFKI Budapest, Hungary, Kurchatov Institute Moscow, Russia, LPC Clermont-Ferrand, France, Korea University, Seoul, Korea, GSI Darmstadt, Germany, IReS Strasbourg, France, FZ Rossendorf, Germany, Univ. of Heidelberg, Germany , Univ. of Warsaw, Poland, RBI Zagreb, Croatia, IMP Lanzhou, China, SMI Vienna, Austria, TUM, Munich, Germany, T.Yamazaki(RIKEN)



and to the ASYEOS collaboration

authors of proposal 2009

Co-Spokespersons: R.C. Lemmon[1] and P. Russotto[2]

List from the Proposal

Collaboration

F. Amorini[2], A. Anzalone[17], T. Aumann[3], V. Avdeichikov[12], V. Baran[23], Z. Basrak[4], J. Benlliure[13], I. Berceanu[11], A. Bickley[14], E. Bonnet[6], K. Boretzky[3], R. Bougault[30], J. Brzychczyk[8], B. Bubak[22], G. Cardella[7], S. Cavallaro[2], J. Cederkall[12], M. Chartier[5], M.B. Chatterjee[16], A. Chbihi[6], M. Colonna[17], D. Cozma[11], B. Czech[10], E. De Filippo[7], K. Fissum[12], D. Di Julio[12], M. Di Toro[2], M. Famiano[27], J.D. Frankland[6], E. Galichet[18], I. Gasparic[4], E. Geraci[15], V. Giordano[2], P. Golubev[12], L. Grassi[15], A. Grzeszczuk[22], P. Guazzoni[21], M. Heil[3], J. Helgesson[31], L. Isaksson[12], B. Jacobsson[12], A. Kelic[3], M. Kis[4], S. Kowalski[22], E. La Guidara[20], G. Lanzalone[29], N. Le Neindre[30], Y. Leifels[3], Q. Li[9], I. Lombardo[2], O. Lopez[30], J. Lukasik[10], W. Lynch[14], P. Napolitani[30], N.G. Nicolis[24], A. Pagano[7], M. Papa[7], M. Parlog[30], P. Pawlowski[10], M. Petrovici[11], S. Pirrone[7], G. Politi[15], A. Pop[11], F. Porto[2], R. Reifarth[3], W. Reisdorf[3], E. Rosato[19], M.V. Ricciardi[3], F. Rizzo[2], W.U. Schroder[28], H. Simon[3], K. Siwek-Wilczynska[26], I. Skwira-Chalot[26], I. Skwirczynska[10], W. Trautmann[3], M.B. Tsang[14], G. Verde[7], E. Vient[30], M. Vigilante[19], J.P. Wieleczko[6], J. Wilczynski[25], P.Z. Wu[5], L.Zetta[21], W. Zipper[22]

FAIR in 2025

Busan in 2018

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